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HOUSTON ASTRONAUTICS DIVISION

SPACE SHUTTLE ENGINEERING AND OPERATIONS SUPPORT

DESIGN NOTE NO. 1.4-4-20

RETURN-TO-LAUNCH-SITE TRAJECTORY SHAPING FOR FIRST STAGE ABORTS

MISSION PLANNING, MISSION ANALYSIS AND SOFTWARE FORMULATION

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## LYNDON B. JOHNSON SPACE CENTER MEMORANDUM

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## 1.0 SUMMARY

This document presents the results of a study to extend the Return-to-Launch-Site (RTLS) flyback trajectory shaping algorithm to first stage aborts. Results are presented which show that the techniques developed for a second stage Space Shuttle Main Engine (SSME) shutdown can be successfully used for a first stage SSME shutdown. The additional software required is twenty-four storage locations, sixteen arithmetic operations and one logic test.

## 2.0 INTRODUCTION

An algorithm was designed to compute the constant inertial thrust attitude angle to be flown during the RTLS fuel dissipation phase in order to merge all RTLS flyback trajectories to a premission reference. This algorithm (presented in Reference (A)) was developed for a second stage shutdown of one SSME and compensated for dispersions at SRB staging. The algorithm uses a set of quadratic coefficients which are determined prior to launch.

This study was conducted to determine the modifications required to extend the algorithm to include the shutdown of one SSME during first stage. The appropriate changes to the reference SRB staging conditions, independent variable, dispersion correction procedure, and quadratic coefficients are discussed. Test cases are presented which verify the extension of the algorithm to include the shutdown of one SSME during first stage.

### 3.0 DISCUSSION

#### 3.1 Explanation of Algorithm

As discussed in Reference (A), the second stage RTLS flyback trajectory shaping algorithm requires a set of reference SRB staging conditions which were chosen to be velocity, flight path angle, and altitude. The reference SRB staging conditions are determined prior to launch by simulating a normal first stage trajectory that uses nominal values to compute performance related variables. The second stage algorithm compares past performance at SRB staging to compensate for dispersions.

The SRB staging conditions that result from a first stage SSME shutdown are functions of the conditions at shutdown. For this reason a new set of reference SRB staging conditions must be computed if a SSME is shutdown and a RTLS is selected. The new reference conditions can be computed from quadratic functions of the relative velocity at SSME shutdown. Predicted reference SRB staging conditions are shown in Figure (1) for Baseline Reference Mission (BRM) 3A. The conditions are consistent with those presented in Reference (B). Similar results were presented in Reference (C).

A change in independent variable is required to extend the algorithm to include first stage SSME shutdowns. The velocity at abort is a good measure of performance during second stage and was chosen as the independent variable in Reference (A). A good measure of first

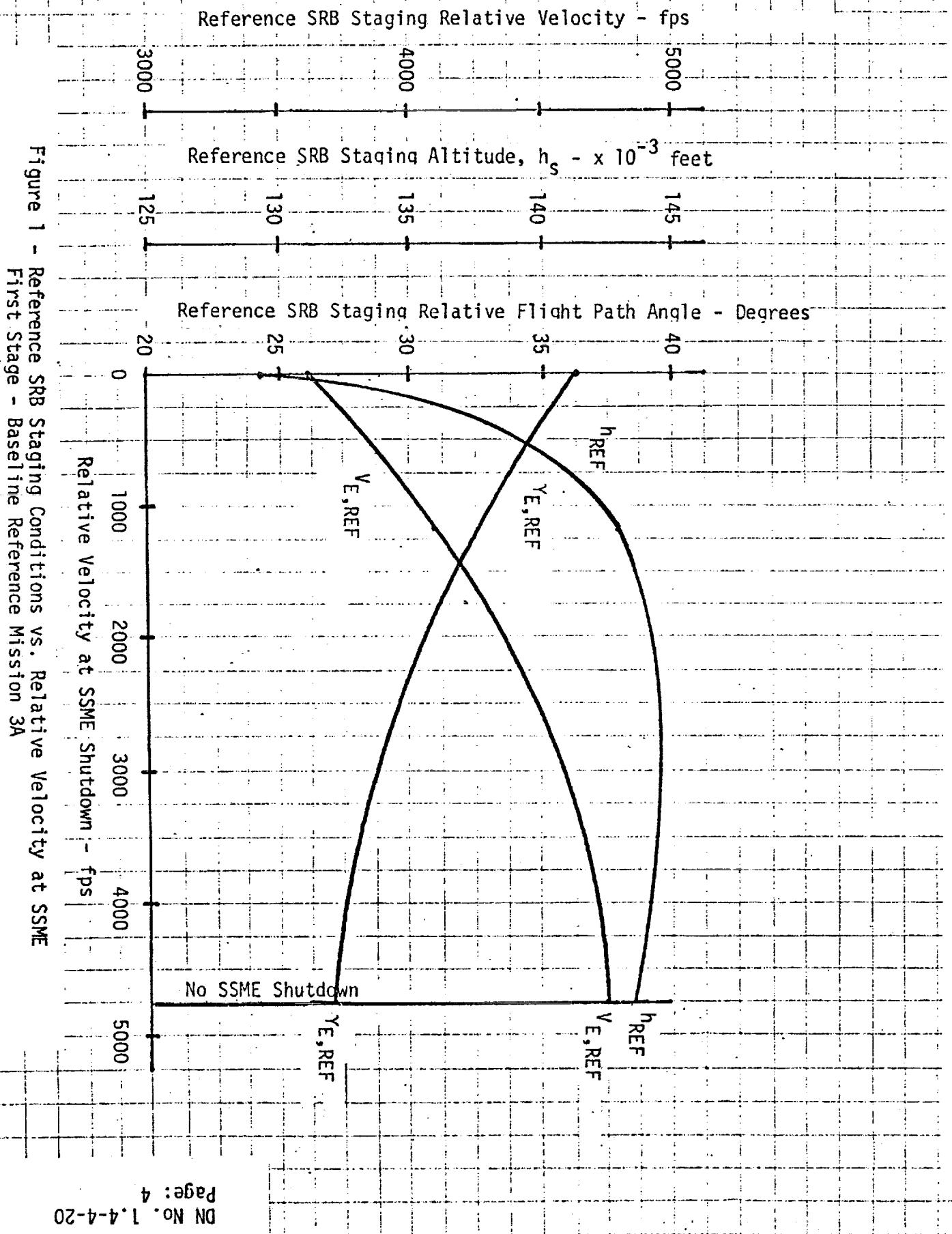


Figure 1 - Reference SRB Staging Conditions vs. Relative Velocity at SSME First Stage - Baseline Reference Mission 3A

stage performance is the actual velocity at SRB staging. Since RTLS guidance commands are not issued until after SRB staging, the SRB staging velocity is used as the independent variable for first stage SSME shutdowns.

A reference fuel dissipation thrust attitude,  $\theta_{REF}$ , is computed as a quadratic function of the appropriate independent variable. Different quadratic coefficients are required for first or second stage computations. The reference attitude will merge the flyback trajectory of the individual RTLS case to that of the RTLS reference trajectory. The reference trajectory is determined by simulating a flyback at the maximum allowable SSME throttle setting from the RTLS mode boundary. All trajectories use nominal values to compute performance related variables.

Appropriate corrections must be applied to  $\theta_{REF}$  when there are dispersions at SRB staging. The partial derivatives required to compute the corrections were derived by the procedure presented in Reference (A). The partial derivatives are fitted by quadratic functions of the appropriate independent variable for first and second stage SSME shutdowns. Different quadratic coefficients are required for each stage.

The velocity dispersion at SRB staging will affect all terms of the algorithm of which  $\theta_{REF}$  and  $\Delta h_{MAX}/\Delta V_{E,S}$  are the most important. The change in  $\theta_{REF}$  caused by a velocity dispersion must not be duplicated in the  $\Delta h_{MAX}/\Delta V_{E,S}$  term.

The velocity correction contained in the computation of  $\theta_{REF}$  in second stage can be shown by writing  $\theta_{REF}$  as

$$\theta_{REF} = \theta_{REF}^* + \frac{\partial \theta_{REF}}{\partial V_{E,AB}} \Delta V_{E,AB}$$

where

$\theta_{REF}^*$  is evaluated at the reference abort velocity for a particular case.

$\Delta V_{E,AB}$  is the difference between the actual velocity and the reference abort velocity

and

$\frac{\partial \theta}{\partial V_{E,AB}}$  is the required change in  $\theta_{REF}^*$  with respect to the change in abort velocity.

The terms on the right hand side of the above equation can not be evaluated since a reference abort velocity is not available to the algorithm. A reference set of SRB staging conditions is available as discussed earlier. The algorithm uses the actual SRB staging conditions to obtain a measure of the dispersions relative to the reference conditions. Since the downrange propagation of a SRB staging velocity dispersion is approximately one to one, part of

the velocity dispersion effect included when  $\theta_{REF}$  is computed as a quadratic function of the actual velocity at abort. A similar effect occurs during a first stage RTLS computation.

The partial derivative  $\Delta h_{MAX}/\Delta V_{E,s}$  is determined by using the particular  $\theta_{REF}$  angle with a perturbed staging velocity. The velocity effect in the  $\theta_{REF}$  term is partially contained in the  $\Delta h_{MAX}/\Delta V_{E,s}$  term. The  $\Delta h_{MAX}/\Delta V_{E,s}$  has been modified to remove the duplicate correction.

During first stage the thrust direction is dependent upon the location of the non-thrusting engine (since the body attitude is commanded) and therefore the actual SRB staging conditions will depend upon which SSME is shutdown. The algorithm computes one set of reference SRB staging conditions and includes the different actual SRB staging conditions as part of the dispersion correction procedure.

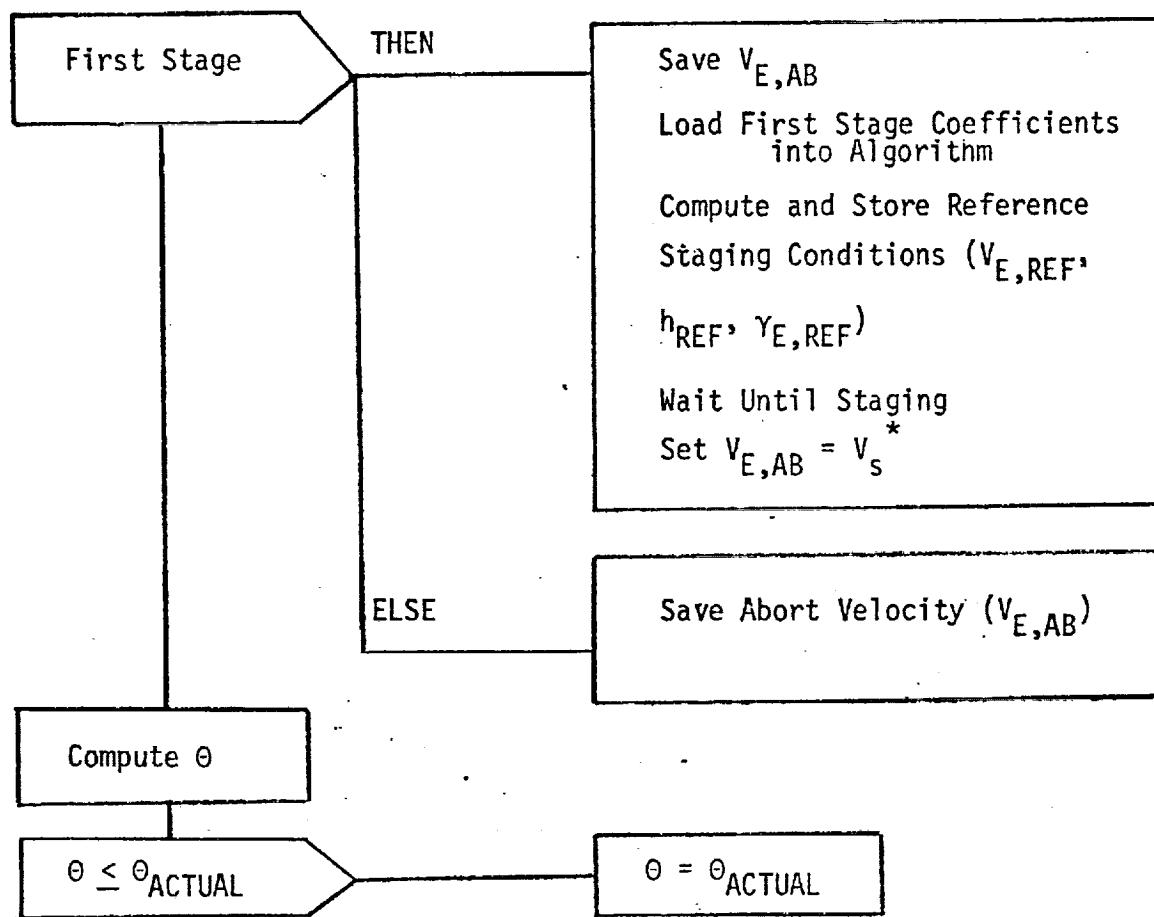
The flow chart of the algorithm is presented in Figure (2). A second stage RTLS is assumed and appropriate prelaunch computed values are loaded into the algorithm. If RTLS is selected during first stage, the abort velocity is saved and used to compute the first stage RTLS reference SRB staging conditions which replace the second stage values. The second stage coefficients are replaced by the first stage coefficients. At staging the independent variable is reset to the actual velocity. This allows the same

Figure 2 - Flow Chart for the Extended RTLS  
Trajectory Shaping Algorithm

PRELAUNCH

Store Reference SRB Staging Conditions  
Store Quadratic Coefficients (load second stage coefficients into algorithm)

SSME SHUTDOWN AND RTLS SELECTED



\* Available from ComPool

code to be used to compute the thrust attitude for either a first or second stage RTLS. A limit test is applied to the thrust attitude as discussed in Reference (A).

The code required to compute the thrust attitude is displayed in Figure (3). The quadratics are coded to use the abort velocity as the independent variable. As discussed above the independent variable is reset to the actual SRB staging velocity for a first stage RTLS. The inertial variables used in Reference (A) have been changed to relative variables.

The software requirements are summarized in Figure (4). The arithmetic operations shown for a first stage RTLS include the computation of the thrust attitude which is also shown for a second stage RTLS. The first stage storage and logic test are in addition to that required for a second stage RTLS. No attempt has been made, at this time, to optimize the code required.

Figure 3 - RTLS Trajectory Shaping Fuel Dissipation  
Inertial Thrust Attitude

$$\theta = \theta_{REF} - \left\{ \left( \frac{\Delta h_{MAX}}{\Delta v_{E,s}} \right) \Delta v_{E,s} + \left( \frac{\Delta h_{MAX}}{\Delta h_s} \right) \Delta h_s \right. \\ \left. + \left( \frac{\Delta h_{MAX}}{\Delta \gamma_{E,s}} \right) \Delta \gamma_{E,s} \right\} / \left( \frac{\Delta h_{MAX}}{\Delta \theta_{REF}} \right)$$

If  $\theta \leq \theta_{ACTUAL}$        $\theta = \theta_{ACTUAL}$

where

$\theta_{ACTUAL}$  = current  $\theta$

$\theta_{REF}$  = reference inertial thrust attitude

$\Delta h_{MAX}/\Delta \theta_{REF}$  = change in maximum altitude with respect to a change in thrust attitude.

s - denotes evaluation at SRB staging.

$v_E$  - relative velocity

$h$  - altitude

$\gamma_E$  - relative flight path angle

$\Delta v_{E,s}$ ,  $\Delta h$ ,  $\Delta \gamma_{E,s}$  - actual minus reference conditions at SRB staging.

The first stage reference conditions ( $v_{E,REF}$ ,  $h_{REF}$ ,  $\gamma_{E,REF}$ )

and the terms

Figure 3 - RTLS Trajectory Shaping Fuel Dissipation  
Inertial Thrust Attitude (Continued)

$$\theta_{REF}, \left( \frac{\Delta h_{MAX}}{\Delta v_{E,s}} \right), \left( \frac{\Delta h_{MAX}}{\Delta h_s} \right), \left( \frac{\Delta h_{MAX}}{\Delta y_{E,s}} \right), \left( \frac{\Delta h_{MAX}}{\Delta \theta_{REF}} \right)$$

were fitted by quadratics. For example, the second stage reference thrust attitude is:

$$\theta_{REF} = 82.45 - 8.8 \times 10^{-3} v_{E,AB} + 3.8 \times 10^{-7} v_{E,AB}^2$$

where

$v_{E,AB}$  - relative velocity at time of abort.

The quadratic coefficients (for the Mission 3A simulation used in the study) are shown in Table I.

	STORAGE LOCATION	LOGIC TEST	ARITHMETIC OPERATIONS	LIMIT TEST
FIRST STAGE	24	1	52*	0
SECOND STAGE	15	0	36	1

\* CODE INCLUDES THE ARITHMETIC OPERATIONS TO COMPUTE  $\theta$  WHICH ARE THE SAME AS SHOWN FOR SECOND STAGE

Figure 4 - RTLS Trajectory Shaping Software Requirements

### 3.2 Verification Technique

This study used a three degree of freedom simulation contained on a modified Space Vehicle Dynamic Simulation (SVDS) 3.0 milestone file (Reference (D)). The RTLS flyback trajectory shaping algorithm was executed off line prior to simulating a particular trajectory.

A normal no wind BRM 3A first stage trajectory was simulated to establish the second stage RTLS reference SRB staging conditions. The trajectory is consistent with the data presented in Reference (B). The RTLS mode boundary reference trajectory was established from these conditions. Selected second stage SSME shutdown times were used to determine the second stage quadratic coefficients.

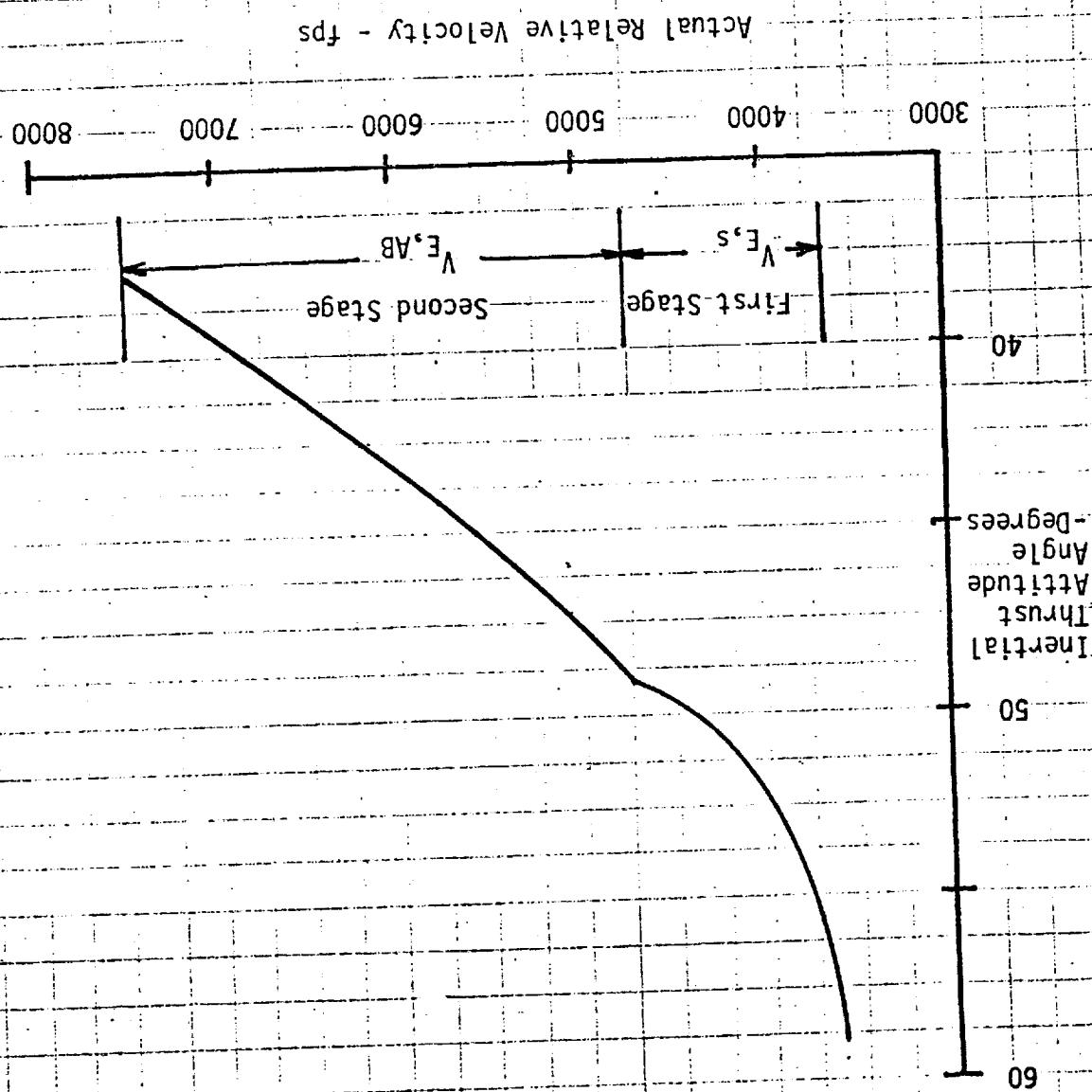
Three cases were used to obtain the reference SRB staging conditions for a first stage RTLS. Two cases (liftoff and 56 second aborts) were obtained from arithmetic averages of the cases presented in Reference (B). The third case was a no wind normal launch. The three sets of SRB staging conditions were used to obtain the first stage quadratics.

The quadratic coefficients are presented in Table I. The reference inertial thrust attitude is shown in Figure (5) and the partial derivatives are shown in Figures (6) and (7). The change in independent variable between first and second stages is shown in the

TABLE I  
QUADRATIC COEFFICIENTS - Mission 3A RTLS Trajectory Shaping

Term	Quadratic Coefficients		
	a	b	c
First Stage			
$\theta_{REF}$	247.1	$-8.510 \times 10^{-2}$	$9.150 \times 10^{-6}$
$\Delta h_{MAX}/\Delta V_{E,s}$	-1895	.8768	$-9.751 \times 10^{-5}$
$\Delta h_{MAX}/\Delta h_s$	2.647	$-6.205 \times 10^{-4}$	$6.051 \times 10^{-8}$
$\Delta h_{MAX}/\Delta \gamma_{E,s}$	4.5120	-13.57	$1.630 \times 10^{-3}$
$\Delta h_{MAX}/\Delta \theta_{REF}$	-62.33	6.785	$-1.044 \times 10^{-3}$
$v_{E,REF}$	3616	.4619	$-4.685 \times 10^{-5}$
$h_{REF}$	129193	14.49	$-2.415 \times 10^{-3}$
$\gamma_{E,REF}$	36.30	$-3.500 \times 10^{-3}$	$3.291 \times 10^{-7}$
Second Stage			
$\theta_{REF}$	82.45	$-8.800 \times 10^{-3}$	$3.800 \times 10^{-7}$
$\Delta h_{MAX}/\Delta V_{E,s}$	328.5	$-8.129 \times 10^{-2}$	$5.598 \times 10^{-6}$
$\Delta h_{MAX}/\Delta h_s$	2.801	$-5.060 \times 10^{-4}$	$2.982 \times 10^{-8}$
$\Delta h_{MAX}/\Delta \gamma_{E,s}$	50650	-9.108	$4.508 \times 10^{-4}$
$\Delta h_{MAX}/\Delta \theta_{REF}$	36340.	-7.885	$4.279 \times 10^{-4}$

Figure 5 - Inertial Thrust Attitude Angle Required  
to Match Mode Boundary Trajectory vs.  
Relative Velocity - Reference Trajectory



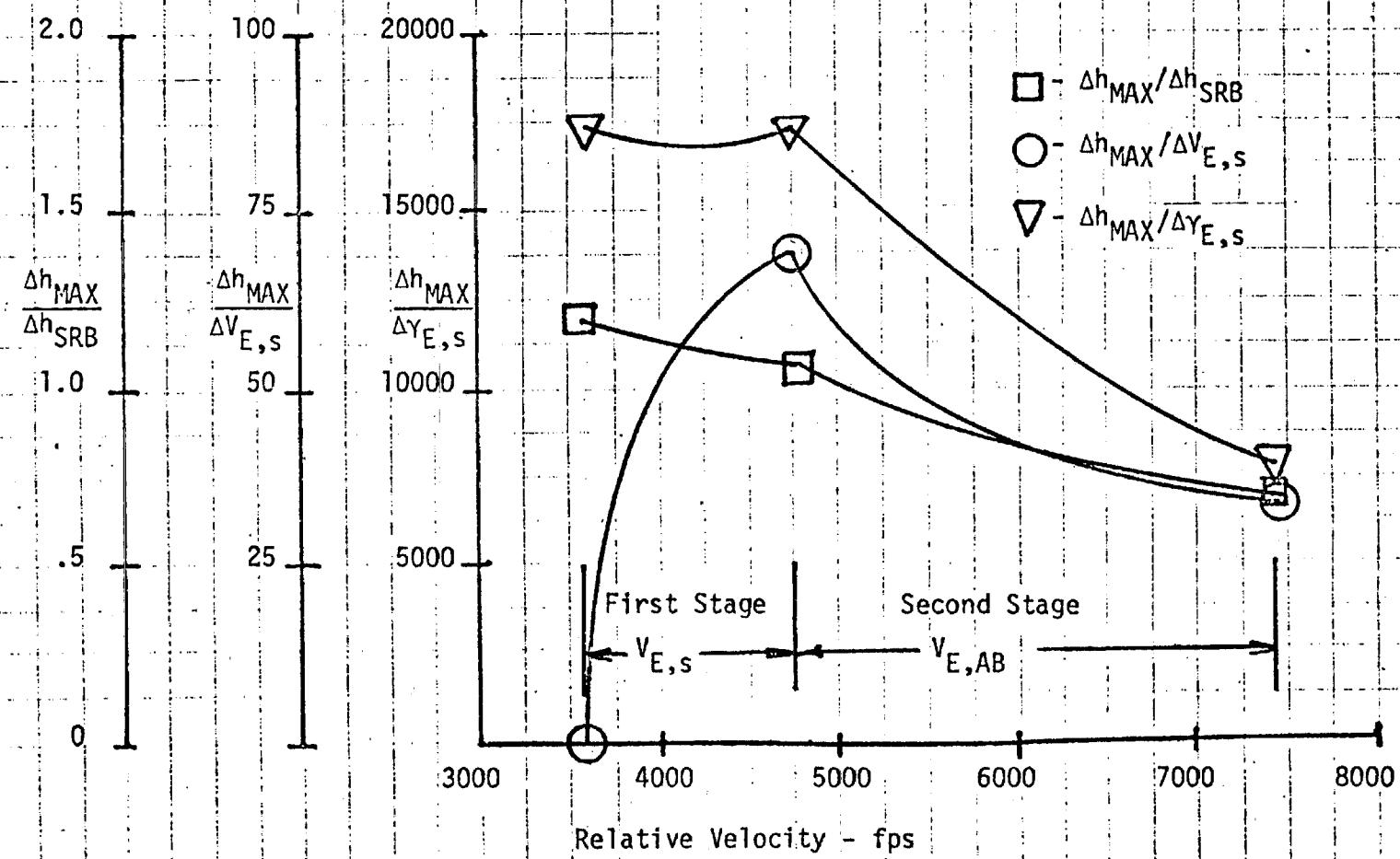


Figure 6 - Change in Maximum Altitude with Respect to Dispersions at SRB Separation

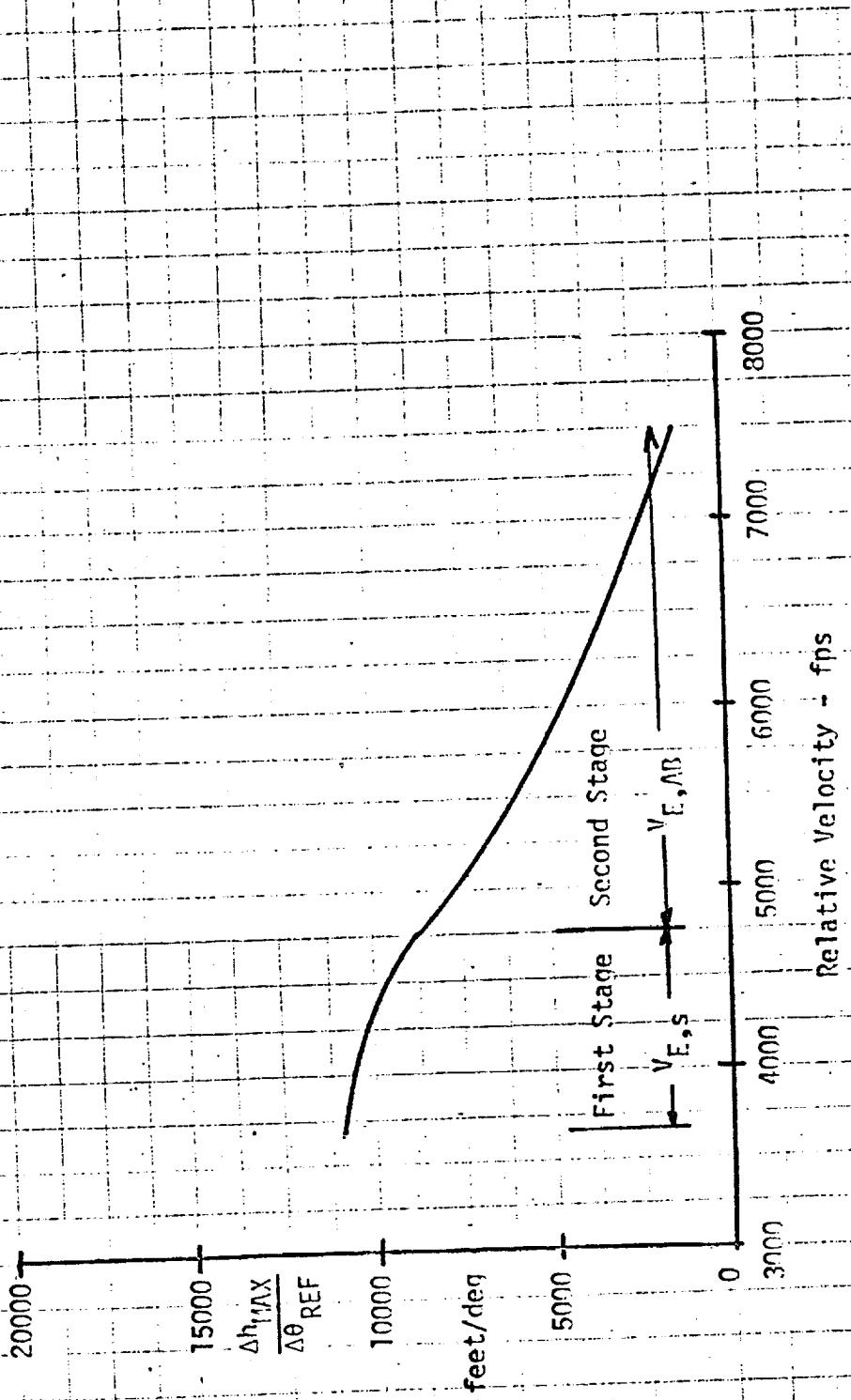


Figure 7 - Change in Maximum Altitude with Respect to Change in Thrust Attitude Angle

figures. The velocity at SRB staging is the terminal velocity for the first stage quadratic functions and it is the initial velocity of the second stage quadratic functions. Therefore the quadratic functions are continuous from first to second stage. The slope of the quadratics are not continuous because different coefficients were used in each stage.

#### 4.0 RESULTS

Merged trajectories are shown in Figures (8) and (9) for reference (non-dispersed SRB staging conditions. Two first stage and four second stage aborts are exhibited. The trajectory conditions for the six cases are summarized in Table II. The Range-Velocity (R-V) arrival points are from 285.6 to 310.8 nautical miles. The 25.2 nautical mile spread compares favorably to the 22.2 nautical mile spread shown in Reference (A).

Merged trajectories are shown in Figures (10) to (12) for dispersed conditions at SRB separation. The first stage aborts are presented in Figures (10) and (11) for an SSME shutdown at liftoff and 56 seconds. The dispersions resulted from cross winds and the location (upper or lower) of the shutdown SSME. The dispersed conditions for a SSME shutdown at SRB staging were obtained from headwind and tailwind cases that are consistent with Reference (B).

The trajectory conditions for the dispersed SRB staging cases are summarized in Table III. The R-V arrival points for the dispersed cases have moved 1.4 to 4.1 nautical miles from the reference cases. The inertial thrust attitude for the SRB staging cases was computed using both the first and second stage coefficients and the results were identical to three significant digits.

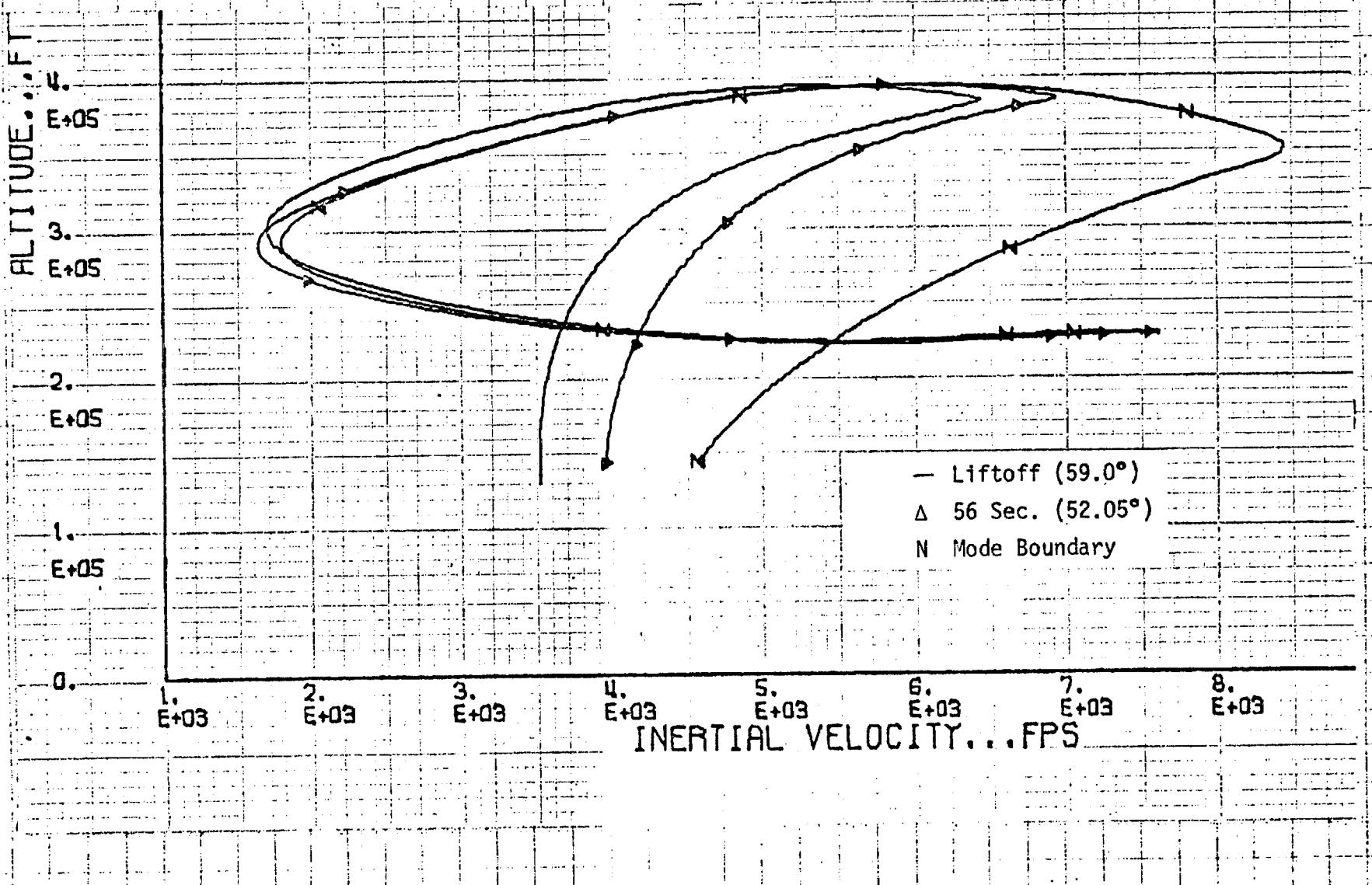


Figure 8 - RTLS Trajectory Shaping Altitude vs Inertial Velocity for Varying Attitude Angles and Abort Time.  
First Stage Reference Trajectories

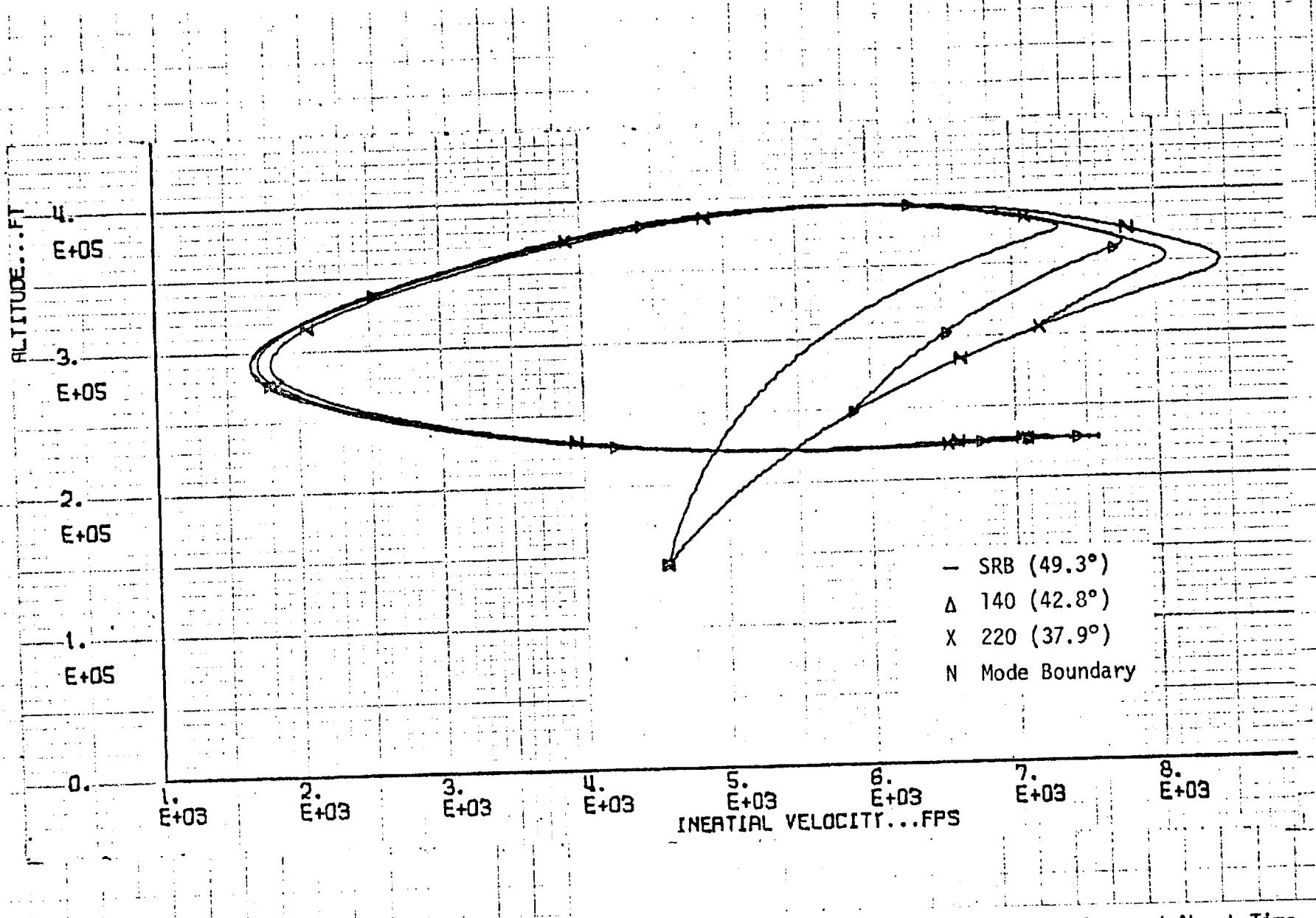


Figure 9 - RTLS Trajectory Shaping Altitude vs Inertial Velocity for Varying Attitude Angles and Abort Time,  
Second Stage Reference Trajectories

TABLE II  
MATCHING TRAJECTORIES - REFERENCE CONDITIONS AT SRB STAGING

Abort Time	V <sub>E</sub> FPS	Conditions at Abort		Attitudes θ DEG	MECO		V <sub>E</sub> FPS
		γ <sub>E</sub> DEG	Alt. FT		R N.M.		
LIFTOFF*	3616	36.3	129193	59.0	303.4	6951	
56 SEC.*	4093	32.65	142860	52.05	310.8	7061	
SRB SEP.	4753	27.10	143510	49.3	309.0	7034	
180 SEC.	6141	15.24	248094	42.8	304.0	6961	
220 SEC.	7473	10.07	305580	37.9	294.7	6824	
250 SEC.	8654	7.53	341449	Immediate Turnaround	285.6	6692	

\* CONDITIONS AT SRB SEPARATION

ALTITUDE... FT

4.  
E+05

3.  
E+05

2.  
E+05

1.  
E+05

0.

1.  
E+03

2.  
E+03

3.  
E+03

4.  
E+03

5.  
E+03

6.  
E+03

7.  
E+03

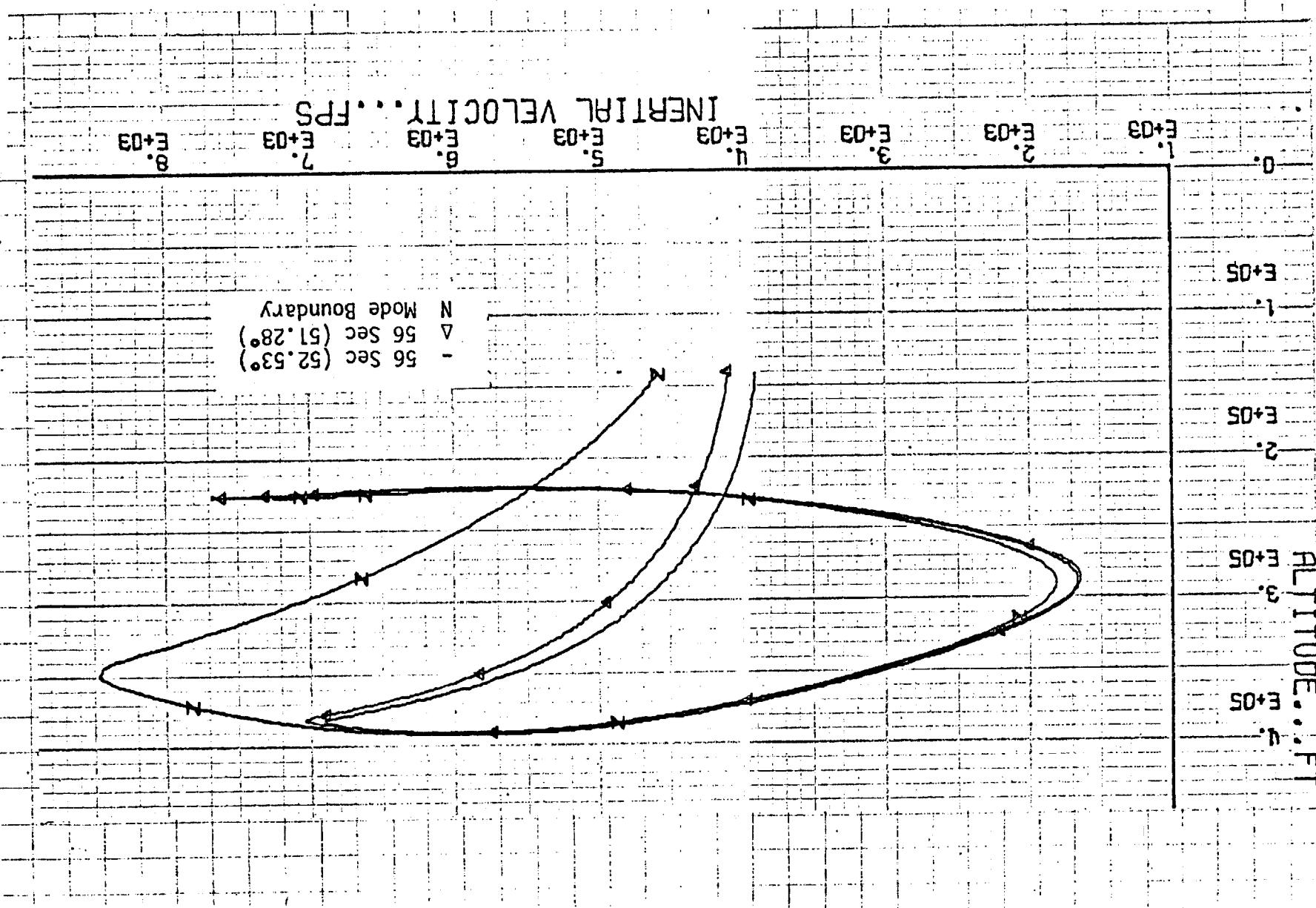
8.  
E+03

INERTIAL VELOCITY... FPS

- Liftoff ( $58.42^\circ$ )
- Δ Liftoff ( $58.97^\circ$ )
- N Mode Boundary

Figure 10 - RTLS Trajectory Shaping Altitude vs Inertial Velocity for SSME Shutdown at Liftoff -  
Dispersed Conditions

Figure 11 - RTLS Trajectory Shaping Altitude vs. Inertial Velocity for SSM  
Shutdown at 56 Seconds - Dispersed Conditions



RTLS TRAJECTORY

E+05

E+05

E+05

E+05

0.

1.  
E+03

2.  
E+03

3.  
E+03

4.  
E+03

5.  
E+03

6.  
E+03

7.  
E+03

8.  
E+03

INERTIAL VELOCITY...FPS

- SRB Headwind ( $48.25^\circ$ )
- $\Delta$  SRB Tailwind ( $49.42^\circ$ )
- N Mode Boundary

Figure 12. - RTLS Trajectory Shaping Altitude vs Inertial Velocity for SSME Shutdown at SRB Staging, Headwind and Tailwind Cases

TABLE III  
MATCHING TRAJECTORIES - DISPERSED CONDITIONS AT SRB STAGING

Abort Time	Conditions at SRB Separation			Attitudes $\Theta$ DEG	MECO	
	V <sub>E</sub> FPS	$\gamma_E$ DEG	Alt. FT		R N.M.	V <sub>E</sub> FPS
LIFTOFF	3528	37.6	131266	58.42	301.0	6917
LIFTOFF	3743	35.07	126183	58.97	307.5	7013
56 SEC.	4026	32.98	143369	52.53	308.8	7031
56 SEC.	4231	31.93	141119	51.28	314.3	7113
SRB SEP Headwind	4886	26.8	142279	48.25	311.9	7077
SRB SEP Tailwind	4680	27.4	144669	49.42	307.6	7014

## 5.0 CONCLUSIONS

The following conclusions can be made concerning the extended RTLS flyback trajectory shaping algorithm:

1. An algorithm has been developed that computes a fuel dissipation inertial thrust attitude to merge RTLS flyback trajectories.
2. The algorithm compensates for SRB staging dispersions.
3. Separate sets of quadratic coefficients are required for first and second stage aborts.
4. The code used to compute the inertial thrust attitude is identical for both first and second stage aborts.

## 6.0 REFERENCES

- (A) MDTSCO Design Note No. 1.4-4-15, "Return-to-Launch-Site Trajectory Shaping", October 17, 1975.
- (B) 14th Abort Panel Meeting, "Shuttle 1st Stage SSME E.O. Ascent Abort Trajectories 6 D-0-F SSFS Mission 3A", S. R. Newman, JSC, February 25, 1976.
- (C) 13th Abort Panel Meeting, "Development of SSME Out First Stage Steering Data", J. D. Moote, RI, November 4, 1975.
- (D) User's Guide for Space Vehicle Dynamic Simulation (SVDS) Program Revision 3, JSC Internal Note No. 73-FM-67, September 26, 1975.